Load Modeling in Optimal Power Flow Studies

A PROJECT THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology
In
Electrical Engineering

By

Sambit Kumar Dwivedi
108EE002

Department of Electrical Engineering
National Institute of Technology, Rourkela
Rourkela- 769008, Odisha

Load Modeling in Optimal Power Flow Studies

A PROJECT THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

Bachelor of Technology
In
Electrical Engineering

By

Sambit Kumar Dwivedi
108EE002

Under the Guidance of
Prof. P.C. Panda

Department of Electrical Engineering
National Institute of Technology, Rourkela
Rourkela- 769008, Odisha

National Institute of Technology

Certificate

This is to certify that the work contained in this thesis, titled **"LOAD MODELING IN OPTIMAL POWER FLOW STUDIES"** submitted by **Sambit Kumar Dwivedi** is an authentic work that has been carried out by him under my supervision and guidance in partial fulfillment for the requirement for the award of Bachelor of Technology Degree in Electrical Engineering at National Institute of Technology, Rourkela.

To the best of my knowledge, the matter embodied in the thesis has not been submitted to any other University/ Institute for the award of any Degree or Diploma.

Place: Rourkela

Date:

Prof. P.C. Panda

Department of Electrical Engineering
National Institute of Technology
Rourkela – 769008

Abstract

The present day scenario of electrical power system engineering mainly encompasses the problems like power paucity, blackout, load shedding, ineptness of meeting the necessary demand of power etc. Hence new power plants are built or old ones are expanded and upgraded. Power flow analysis plays an integral role in both the above cases. Power flow analysis equips power system engineers with all the essential data for building a secure, stable and reliable power system.

Power flow analysis tells about the line flows of active and reactive power and bus bar values of voltage magnitude and phase difference. The practical application of load flow analysis is exploited by converting it to Optimal Power Flow (OPF) analysis.

There has been significant development in research fields of power generation plants and transmission and distribution systems. Although these developments play a key role in today's scenario, there still remains a field where the scope of development still persists. Loads in general are taken as constant sinks for both active and reactive power; where in reality, the load power consumption is very much dependent on voltage magnitude and frequency deviations.

OPF analysis incorporating load modeling is a major tool for minimizing transmission and generation losses, generation cost and maximizing the system efficiency. System security and accuracy are also increased by incorporation of load models.

This thesis focuses on incorporating load models in traditional OPF studies and comparing the results of the above with those obtained from OPF analysis without the incorporation of load models.

Acknowledgement

I am grateful to The Department of Electrical Engineering, for giving me the opportunity to carry out this project, which is an integral fragment of the curriculum in B. Tech program at the National Institute of Technology, Rourkela. I would like to express my heartfelt gratitude and regards to my project guide, Prof. Dr. P. C. Panda, Department of Electrical Engineering, for being the corner stone of my project. It was his incessant motivation and guidance during periods of doubts and uncertainties that has helped me to carry on with this project. I would like to thank Prof. B.D. Subudhi, Head of the Department, Electrical Engineering for his guidance, support and direction. I am also obliged to the staff of Electrical Engineering Department for aiding me during the course of our project. I offer my heartiest thanks to my friends for their help in collection of data samples whenever necessary. Last but not the least, I want to acknowledge the contributions of my parents and family members, for their constant and never ending motivation.

SAMBIT KUMAR DWIVEDI
(108EE002)

Table of Contents

List of Tables

List of Figures

CHAPTER 1

Introduction

1.1 Introduction

Electric power utilization must be improved in present scenario while taking into account the security and reliability of power flow. Overall voltage profiles are deteriorated and system stability and security are decreased due to the reason that, transmission line powers flows are not uniform. In some lines it's below the standard value whereas in some it's way above the normal power flow values. Due to this the low voltage condition comes into picture and hence most of the electrical loads are connected to low voltage power distribution systems.

Electrical loads of a system can be told to be comprising of various residential, industrial and municipal loads. Practically the active and reactive powers of loads of a distribution system are dependent on system voltage and frequency variations. Also, the active and reactive power characteristics of various types of load differ from each other. Frequency deviation is considered insignificant in case of static analysis like, load flow studies. The effects of voltage deviations are mainly taken into account for getting faster and accurate results. The results improve the quality of all following system studies that use the same load flow analysis for further calculations and simulations.

In conventional load flow studies, it is presumed that the active and reactive power demands are specified constant values, independent of the voltage values. Though in reality, the various kind of residential, commercial and industrial loads don't provide a constant demand of active and reactive power.

The variation of active and reactive powers depend on voltage magnitude and frequency deviations of the system. This effects, if taken into account can cause major changes in the results of load flow and optimal power flow studies.

The difference in fuel costs are most pronounced when voltage dependent load models are incorporated in **Optimal Power Flow (OPF)** studies. The active and reactive power demands, the losses and the voltage magnitudes are also affected.

1.2 Advantages of Load Modeling in OPF

The advantages of load modeling in OPF are as follows.

- Actual calculation of active and reactive power demand at respective buses.
- Variation of power demand with voltage enables better control capacity.
- Control of over and under voltage at load buses.
- Minimization of losses.
- Improvement in voltage profile.

- Reduction of Incremental Fuel Cost.

1.3 Project Objective

The objective of this project is to develop a voltage dependent load model in which active and reactive powers vary as a function of voltage and to implement this model in Optimal Power Flow studies to minimize the loses and fuel cost.

Chapter 2

Optimal Load Flow Studies

2.1 Introduction

In power system context Load Flow study is steady state solution of the power system network. The important information obtained from this study are essentially the magnitudes and phase angles of load bus voltages, active and reactive powers at generator bus, real power flow on transmission lines and voltage phase angles at specified bus bars. The information obtained from the above analysis are mainly used in continuous monitoring of the present state of the system and for analyzing the effectiveness, security constraints and economic considerations of alternative plans for future system expansion in order to achieve the increased demand of load.

Load flow solution is the primary requirement for designing a new power system and for planning an extension of the existing one for increasing demand. These analyses require a large number of load flow solutions under both normal and abnormal (outage of transmission line or outage of some generators) operating conditions. In case of study of the transient behavior of the system, the initial conditions are provided by load flow analysis.

Steps mentioned below are followed for obtaining the load flow analysis of any given system:

1. Formulation of equations of the given network.

2. Selection of suitable mathematical technique/procedure for the solution of the above equations.

Under steady state condition, the network equations are in the form of simple algebraic equations. The loads and generations continuously change in a real power system, but for solution of load flow equations, it is assumed that loads and generations are fixed for a particular value over suitable periods of time. E.g. an hour/monthly etc. depending upon data.

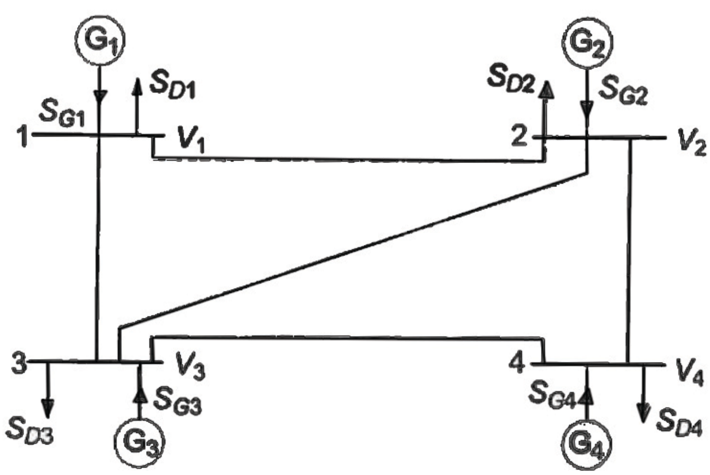

Fig 1: A 4 Bus System

2.1.1 Purpose of Load Flow Analysis

The purpose of Load Flow analysis is

- Voltage magnitudes and angles at all nodes of the feeder.
- Line flow in each line section specified in Kilo Watt (KW) and KVAr, amperes and degrees or amperes and power factor.
- Loss of power in each line section.
- Total feeder input Kilo Watt (KW) and KVAr.
- Total feeder power losses.
- Load Kilo Watt (KW) and KVAr based upon the defined model for the load.

2.2 Types of Buses

The buses in power system are mainly classified into the following categories.

- PQ bus
- PV bus or Generator bus or Voltage Controlled bus
- Slack Bus/Swing bus/Reference bus

2.2.1 Classification of Buses

PQ bus

In this type of bus the net powers active power (P_i) and reactive power (Q_i) are known. The unknowns are voltage magnitude ($|V_i|$) and phase angle (δ_i).

PV bus

In this type of bus active power (P_i) and voltage magnitude ($|V_i|$) are known. So reactive power (Q_i) and phase angle (δ_i) are to be found out. These buses are also known as generator buses or voltage controlled buses. The limits on the value of reactive power are specified at these buses.

Slack bus

This bus is distinguished from other two types by the fact that real and reactive powers (P_i & Q_i) at this bus are not specified. The specified quantities are voltage magnitude and phase angle ($|V_i|$ & δ_i) where as the others are to be found out. Normally there is only one bus of this kind in a given power system. This bus is also known as swing bus or reference bus. This bus makes up the difference between scheduled loads and generated power that are caused by losses in the network.

2.3 Expression for Active and Reactive Power

$$P_i(Active\ Power) = |V_i| \sum_{k=1}^{\infty} |V_k||Y_{ik}| \cos(\theta_{ik} + \theta_k - \delta_j)$$

$$Q_i(Reactive\ Power) = -|V_i| \sum_{k=1}^{\infty} |V_k||Y_{ik}| \sin(\theta_{ik} + \theta_k - \delta_j)$$

i= 1,2,3……n

2.4 Load Flow Solution Methods

Following methods are used for the solution of a Load Flow Problem.

- Gauss-Seidel Method
- Newton-Raphson Method
- Fast-Decoupled Method

2.4.1 Gauss-Seidel Method

Gauss-Seidel method is a method used to solve a linear system of equations. The technique is named after the German mathematicians Carl Friedrich Gauss and Philipp Ludwig von Seidel. The method is an upgraded version of the Jacobian method. It is defined for matrices with non-zero diagonals, but convergence is only achieved if the matrix is either diagonally dominant or symmetric and positive definite. The Gauss-Seidel(GS) method is an iterative method for solving a set of non-linear algebraic equations. In starting, a solution vector is assumed. One of the equation is then used to obtain the revised value of a particular variable by substituting in it the present value of remaining variables. The same process is followed for all the variables completing one complete iteration. The process is then repeated till the solution vector converges within defined accuracy. The convergence is quite sensitive to the starting values that are assumed. In a load flow study a starting vector close to final solution can be easily identified from previous experience.

$$V_i = \frac{1}{Y_{ii}}\left[\frac{P_i - jQ_i}{V_i^*} - \sum_{k=1}^{n} Y_{ik}\, V_k\right]$$

i= 1,2,3……n

2.4.2 Newton - Raphson Method

For an N-bus power system there will be n equations for real power injection P_i and n-equations for reactive power injection Q_i. The number of equations to be solved depends upon the given. If the total number of buses is n and number of generator buses is m then the number of equations to be solved will be number of known P_i's and number of known Q_i's. In the given conditions number of known P_i's are n-1 and the number of known Q_i's are (n-m), therefore the total number of simultaneous equations will be 2*(n-m-1), and number of unknown quantities are also 2*(n-m-1). The unknowns to be calculated are power angles (δ) at all the buses except slack (i.e. n-1) and bus voltages (V) at load bus (i.e. n-m).

$$\begin{pmatrix}\Delta P\\ \Delta Q\end{pmatrix} = \begin{pmatrix}\frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V}\\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V}\end{pmatrix}\begin{pmatrix}\Delta \delta\\ \Delta V\end{pmatrix}$$

$$\Delta P_i = P_i(specified) - P_i$$

$$\Delta Q_i = Q_i(specified) - Q_i$$

Terms of real power will be calculated for all the buses besides the slack bus and reactive power terms shall be calculated for all the load buses. In the above equation

$$\begin{pmatrix} \Delta P \\ \Delta Q \end{pmatrix} \text{ is the mismatch vector}$$

$$\begin{pmatrix} \Delta \delta \\ \Delta V \end{pmatrix} \text{ is the correction vector}$$

and

$$J = \begin{pmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial V} \end{pmatrix} \; is\ the\ Jacobian\ Matrix$$

2.4.3 Fast Decoupled Method

The Fast decoupled power flow solution requires more iterations than the Newton-Raphson technique, but requires significantly less time per iteration and a power flow solution is obtained quickly. This method is very helpful in contingency analysis where numerous outages are to be simulated or a power flow solution is required for on-line control.

2.5 System Constraints

There are two types of constraints.

- Equality constraints.
- Inequality constraints.

Inequality constraints in other hand are again divided into further two categories, i.e. 1) Hard Type and 2) Soft Type. The hard type constraints are fixed and definite for example the tapping range of an on load tap changing transformer. These constraints don't entertain any rigid change in their values, whereas the soft type are those, which offer some flexibility in changing their values, for example nodal voltages and phase angles.

2.5.1 Equality Constraints

The basic load flow equations are the equality constraints.

$$P_p = \sum_{q=1}^{n} \{e_p(e_q G_{pq} + f_q B_{pq}) + f_p(f_q G_{pq} - e_q B_{pq})\}$$

$$Q_p = \sum_{q=1}^{n} \{f_p(e_q G_{pq} + f_q B_{pq}) - e_p(f_p G_{pq} - e_q B_{pq})\}$$

Where,

f_p, e_p are real and imaginary components of voltage at the p^{th} and q^{th} components of voltage at the p^{th} node.

G_{pq}, B_{pq} are the nodal conductance and susceptance between the p^{th} and q^{th} nodes.

2.5.2 Inequality Constraints

The inequality constraints are further divided into following categories.

1. Generator constraints.
2. Voltage constraints.
3. Running spare capacity constraints.
4. Transformer tap settings.
5. Transmission line constraints.
6. Network security constraints.

2.6 Optimal Power Flow

In a practical power system, the generating stations are never located at the same distance from the center of loads and their fuel costs are also different. Also, under normal operating conditions, the generation capacity is more than total demand and losses. Thus, there are many different options for scheduling generation. In a linked (interconnected) power system, the main objective is to track down the real and reactive power scheduling of each power plant in such a way as to reduce the operating cost. This means that the generator's active and reactive power are free to vary within defined limits so as to meet a particular load demand with a lowest possible operating cost. This is called Optimal Power Flow (OPF) problem.

The optimal system operation involves the considerations of economy of operation, system security, fossil fuel plant emissions and optimal release of water at hydro generation plants. The main aim in the economic dispatch problem is to minimize the total cost of generating real power (production cost) at various stations while satisfying the loads and the loses in transmission links.

2.6.1 Generator Operating Cost

The factors influencing power generation at minimum cost are operating efficiencies of generators, cost of fuel, and transmission losses. The most efficient generator of the system doesn't guarantee minimum cost, as it may be placed in an area where fuel cost is high. Transmission losses are considerably higher if the plant is located far from the center of distribution. Hence, the problem is to regulate the generation of different plants such that total operating cost is lowest.

The major component of generator cost is the fuel input/hour while the maintenance contributes a little amount.

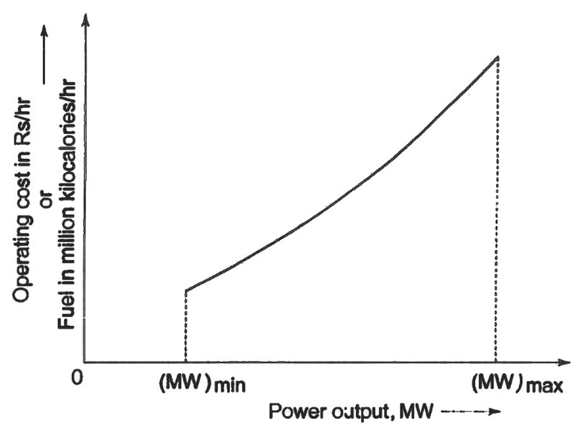

Fig 2: Input-Output curve of a generator

This curve can be fitted into a polynomial equation, which gives the formula for cost calculations

$$J_f = \sum_{i=1}^{k} \alpha_i + \beta_i P_{gi} + \gamma_i {P_{gi}}^2$$

Where,

k= the number of generator buses.

$\alpha_i, \beta_i, \gamma_i =$ fuel cost parameters of the generating source at ith bus.

$P_{gi} =$ Active Power generation at ith bus.

The slope of the above curve represents the incremental fuel cost (IC).

$$\frac{dJ_f}{dP_{gi}} = 2\gamma_i P_{gi} + \beta_i$$

The IC is a measure of how costly it will be to produce the next increment of power.

2.6.2 Optimal Unit Commitment (UC)

It's not economical to run all the units available all the time. In order to determine the units of a plant that should operate for a particular load is the problem of unit commitment. This problem is of importance for thermal plants mainly. Sometimes priority ordering is done to deal with the problem of UC, where the generators are loaded according to their efficiencies, i.e. the most efficient generator is loaded first and so on and so forth. Dynamic programming is another method for solving the UC problem.

2.6.3 Optimum Generation Scheduling

This section deals with the sharing of loads between various plants. The overall cost of generation should be minimized taking into account equality constraints and losses.

$$J = \sum_{i=1}^{k} J_i(P_{gi})$$

subject to the equality constraint

$$\sum_{i=1}^{k} P_{gi} - P_D - P_L = 0$$

Where,

K= total no of generating plants.

$P_{gi} =$ Active Power generation at ith bus.

P_D = Sum of all Load Demands

P_L = Total system Transmission Loss

Again, Total system Transmission loss is given by

$$P_L = \sum_{m=1}^{k} \sum_{n=1}^{k} P_{gm} B_{mn} P_{gn}$$

Where,

P_{gm}, P_{gn} = Real Power generation at m, nth plants

B_{mn} = Loss Co − efficients which are constant under operational conditions

2.7 Summary

This chapter throws light upon some of the basics of Load Flow studies and Optimal Load Flow problem. The basic methods of solving a Load flow problems were discussed and the theory of OPF was described. Along with the theories the formulae representing the Real and Reactive power, transmission line losses were described. This chapter sets the stone for our actual purpose of load modeling and implementing the same in OPF problem

Chapter 3

Load Modeling

3.1 Importance of Load Modeling

The power system engineer bases choices concerning system reinforcements and system performance in large part on the outputs of power flow and stability simulation studies. Representation insufficiency that cause under or over voltage building of the system or decay of reliability could prove to be very much costly. For performing power system analysis, models must be improvised for all pertinent system components, including generation plants, sub stations, transmission and distribution equipment, and load devices. Much importance has been given to models for generation and transmission or distribution equipment. The representation of the load models has received very less attention and persists to be an area of greater uncertainty and carries a scope of very high development. Studies have shown that load representation and load modeling can have significant impact on analysis results. Therefore, efforts directed at upgrading load-modeling provisions are of major importance.

3.2 Classification of Load Models

Load models are basically classified into two broad categories, static models and dynamic models.

3.2.1 Static Load Models

These models express the active and reactive powers, at particular instant of time, as a function of the bus voltage magnitude and frequency. Static load models are used both in static and dynamic load components. The static load is model is given as as an exponential function of voltage, V.

$$P_D = P_o\left(\frac{V}{V_o}\right)^{\alpha}$$

$$Q_D = Q_o\left(\frac{V}{V_o}\right)^{\beta}$$

where,

P_D: load active power

Q_D: load reactive power

P_o: active power consumption at rated voltage, Vo

Q_o: reactive power consumption at rated voltage, Vo α: active power exponent

β: reactive power exponent

V: supply voltage Vo: rated voltage

Table 1: Value of α & β for different Loads

Load component	*np*	*nq*
Battery charge	2. α	4.(β
Fluorescent lamps	2.07	3.21
Constant impedance	2.00	2.00
Fluorescent lighting	1.00	3.00
Air conditioner	0.50	2.50
Constant current	1.00	1.00
Resistance space heater	2.00	0.00
Pumps, fans other motors	0.08	1.60
Incandescent lamps	1.54	0.00
Compact fluorescent lamps	1.00	0.35
Small industrial motors	0.10	0.60
Large industrial motors	0.05	0.50
Constant power	0.00	0.00

3.2.2 Dynamic Load Models

A Dynamic load model expresses the active and reactive powers at any instant of time as functions of the voltage magnitude and frequency. Studies of voltage stability, inter area oscillation, and long term stability often require load dynamic to be modeled. Difference or differential equations can be used to represent such models.

Input-Output Form

$$T_p \dot{P_D} + P_D = P_S(V) + K_P(V)\dot{V}$$

$$T_p \dot{Q_D} + Q_D = Q_S(V) + K_Q(V)\dot{V}$$

$$K_P(V) = T_p P_t(V)'$$

$$K_Q(V) = T_q Q_t(V)'$$

$$P_s = P_o \left(\frac{V}{V_o}\right)^{\alpha_s}$$

$$Q_s = Q_o \left(\frac{V}{V_o}\right)^{\beta_s}$$

$$P_t = P_o \left(\frac{V}{V_o}\right)^{\alpha_t}$$

$$Q_t = Q_o \left(\frac{V}{V_o}\right)^{\beta_t}$$

State Form

$$T_p \dot{X}_p = P_S(V) - P_D$$

$$T_q \dot{X}_q = Q_S(V) - P_D$$

$$P_D = X_p + P_t(V)$$

$$Q_D = X_q + Q_t(V)$$

Where,

T_p: active load recovery time constant

T_q: reactive load recovery time constant

P_D: active power consumption model

Q_D: reactive power consumption model

$P_S(V)$: steady-state part of active power consumption

$Q_S(V)$: steady-state part of reactive power consumption

$P_t(V)$: transient part of active power consumption

$Q_t(V)$: transient part of reactive power consumption

α_s: steady-state active load-voltage dependence

β_s: steady-state reactive load-voltage dependence

α_t: transient active load-voltage dependence

β_t: transient reactive load-voltage dependence

P_o: active power consumption at rated voltage, Vo

Q_o: reactive power consumption at rated voltage, Vo

V: supply voltage

V_o: pre-fault of supply voltage

3.2.3 Composite Load Models

The composite load model can be used to include the influence of various components. It consists of a static load (LS), a generic dynamic recovery load (LG) and an aggregate induction motor load (LIM). The static load represents all the static parts of the load. The generic recovery load is to account for the effects of all down stream On-Load Tap Changer (OLTC) actions and the thermo-statically controlled heating loads. An induction motor is used to represent all down stream compressors and other rotating loads.

$$T_p \frac{dP_r}{dt} + P_r = N_p(V)$$

$$N_p(V) = P_o\left(\frac{V}{V_o}\right)^{\alpha_s} - P_o\left(\frac{V}{V_o}\right)^{\alpha_t}$$

$$P_d = P_r + P_o\left(\frac{V}{V_o}\right)^{\alpha_t}$$

$$T_q \frac{dQ_r}{dt} + Q_r = N_q(V)$$

$$N_q(V) = Q_o\left(\frac{V}{V_o}\right)^{\beta_s} - Q_o\left(\frac{V}{V_o}\right)^{\beta_t}$$

$$Q_d = Q_r + Q_o\left(\frac{V}{V_o}\right)^{\beta_t}$$

Where,

T_p: active load recovery time constant

T_q: reactive load recovery time constant

P_o: active power consumption at pre-fault voltage

Q_o: reactive power consumption at pre-fault voltage

P_d: active power consumption model

Q_d: reactive power consumption model

P_r: active power recovery

Q_r: reactive power recovery

α_s: steady-state active load-voltage dependence

β_s: steady-state active load-voltage dependence

α_t: transient active load-voltage dependence

β_t: transient active load-voltage dependence

V: supply voltage

V_o: pre-fault of voltage

3.3 Different type of Static and Dynamic of Load Models

Following are some of the categories of static and dynamic load models.

- **Constant Impedance Load Model** is a static load model where the power has a square relationship with the voltage magnitude. It may also be called as a constant admittance model.
- **Constant Current Load Model** is a static model where the power varies directly with voltage magnitude
- **Constant Power Load Model** is a static load model where power doesn't change with voltage magnitude. It can also be called constant MVA model.

- **Polynomial Load Model** is a static load model which represents the relationship of voltage magnitude with power as a polynomial.

$$P = P_o \left[a_o \left(\frac{V}{V_o} \right)^2 + a_1 \left(\frac{V}{V_o} \right) + a_2 \right]$$

$$Q = Q_o \left[b_o \left(\frac{V}{V_o} \right)^2 + b_1 \left(\frac{V}{V_o} \right) + b_2 \right]$$

where

$$a_o + a_1 + a_2 = 1$$
$$b_o + b_1 + b_2 = 1$$

This model is sometimes called "ZIP" model as it represents all the above models in a single equation.

- **Exponential Load Model** is a static model where power is represented with an exponential expression of voltage.

3.4 Incorporation of Static Load Model

Newton-Raphson method written in its polar co-ordinates form is ideally suited for incorporating the load model for load flow solution.

$$P_D = P_o \left(\frac{V}{V_o} \right)^{\alpha}$$

$$Q_D = Q_o \left(\frac{V}{V_o} \right)^{\beta}$$

Differentiating the above equations wrt V

$$\frac{\partial P_D}{\partial V} = P_o\, \alpha \left(\frac{V}{V_o} \right)^{\alpha-1} \frac{1}{V_o} + \frac{\partial P_o}{\partial V} \left(\frac{V}{V_o} \right)^{\alpha} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

$$\frac{\partial Q_D}{\partial V} = Q_o\, \beta \left(\frac{V}{V_o} \right)^{\beta-1} \frac{1}{V_o} + \frac{\partial Q_o}{\partial V} \left(\frac{V}{V_o} \right)^{\beta} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

it's been mentioned before

$$\frac{\partial P_o}{\partial V} = 2|V_i||Y_{ii}|\cos(\delta_{jj}) + \sum_{k=1}^{\infty}|V_k||Y_{ik}|\,cos(\theta_{ik} + \theta_k - \delta_j)\ldots.(3)$$

$$\frac{\partial Q_o}{\partial V} = 2|V_i||Y_{ii}|\cos(\delta_{jj}) + \sum_{k=1}^{\infty}|V_k||Y_{ik}|sin(\theta_{ik} + \theta_k - \delta_j)\ldots.(4)$$

Substituting (3) in (1)

$$\frac{\partial P_D}{\partial V} = P_o\,\alpha\left(\frac{V}{V_o}\right)^{\alpha-1}\frac{1}{V_o} + 2|V_i||Y_{ii}|\cos(\delta_{jj}) + \sum_{k=1}^{\infty}|V_k||Y_{ik}|\,cos(\theta_{ik} + \theta_k - \delta_j)$$

Similarly substituting (4) in (2)

$$\frac{\partial Q_D}{\partial V} = Q_o\,\beta\left(\frac{V}{V_o}\right)^{\beta-1}\frac{1}{V_o} + 2|V_i||Y_{ii}|\cos(\delta_{jj}) + \sum_{k=1}^{\infty}|V_k||Y_{ik}|sin(\theta_{ik} + \theta_k - \delta_j)$$

The above two equations form the base of further calculations. The above equations are further used foe calculating the jacobian and hence to carry out OPF.

Chapter 4

Load Modeling Simulation and results

4.1 Problem Statement

For the above project an IEEE 14 bus system is taken and analyzed with both constant and voltage dependent load models. The simulations are carried out using a Matlab Power system toolbox known as PSAT (Power System Analysis Toolbox). The results from the simulations are plotted in MS Excel and further analyzed.

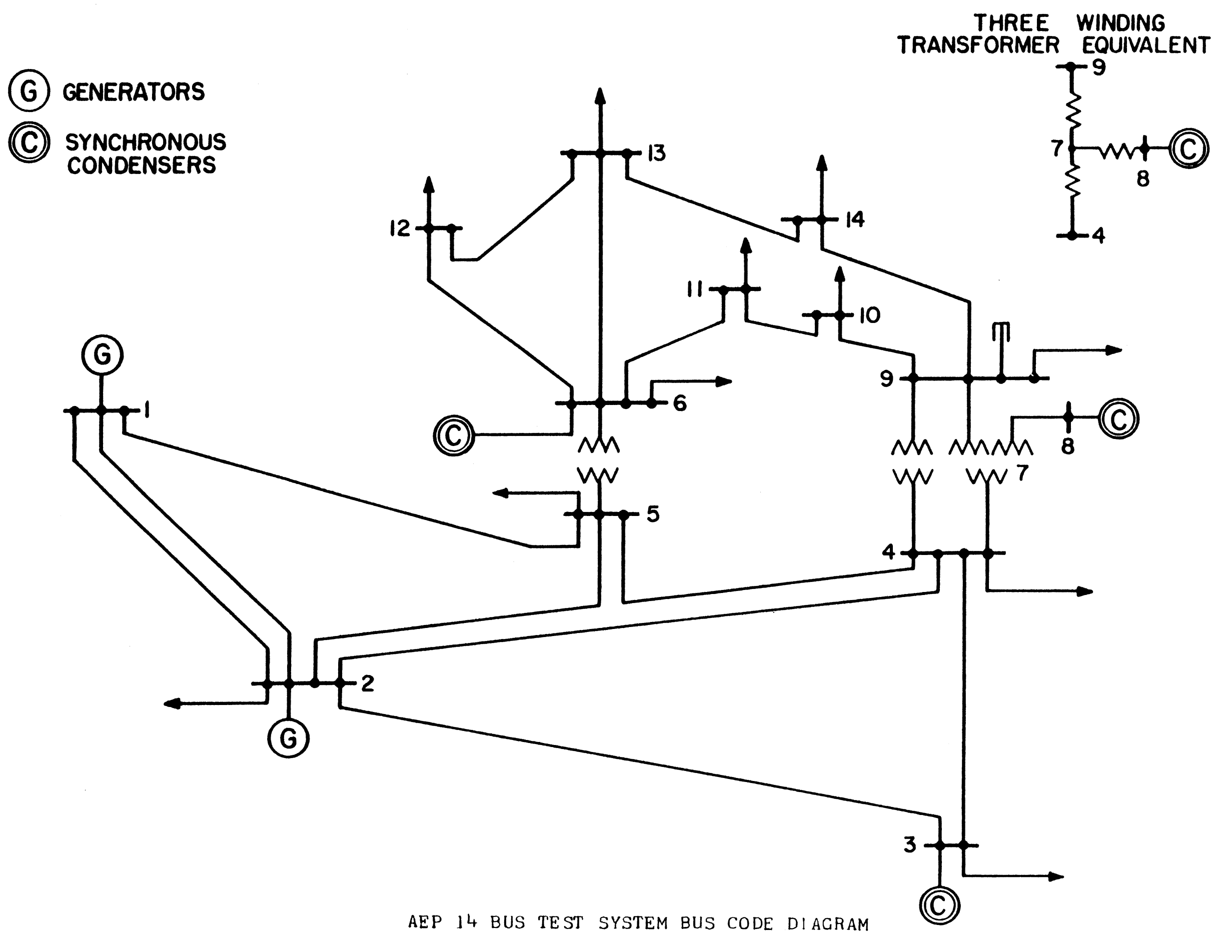

Fig 3: A standard IEEE 14 bus system

The figure shown above is that of a standard IEEE 14 bus system. The above figure is simulated using the Simulink model which include blocks from the Matlab toolbox PSAT.

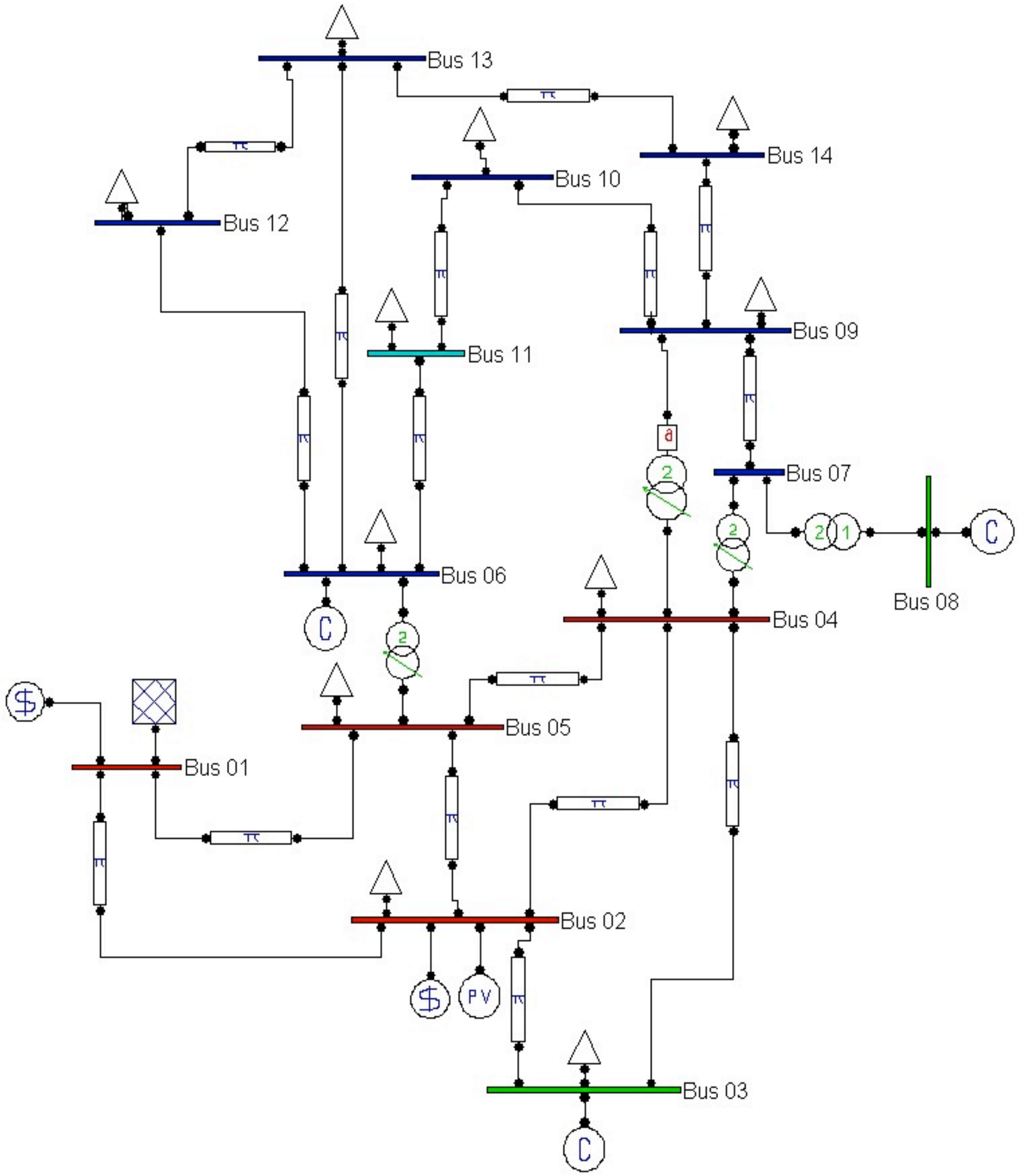

Fig 4: Simulink model of IEEE 14 bus system without voltage dependent loads

The line data required for the above simulation are given in the tables below.

Table 2: Line Data for IEEE 14 bus system

Bus No	Bus No	Resistance (Per Unit)	Reactance (Per Unit)	Susceptance (Per Unit)
1	2	0.01938	0.05917	0.0528
1	5	0.05403	0.22304	0.0492
2	3	0.04699	0.19797	0.0438
2	4	0.05811	0.17632	0.0374
2	5	0.05695	0.17388	0.034
3	4	0.06701	0.17103	0.0346
4	5	0.01335	0.04211	0.0128
6	11	0.09498	0.1989	0.00
6	12	0.12291	0.25581	0.00
6	13	0.06615	0.13027	0.00
7	9	0.00	0.11001	0.00
9	10	0.03181	0.0845	0.00
9	14	0.12711	0.27038	0.00
10	11	0.08205	0.19207	0.00
12	13	0.22092	0.19988	0.00
13	14	0.17093	0.34802	0.00

Table 3: Generator Data of IEEE 14 Bus System

Bus No	Voltage Magnitude (Per Unit)	Minimum Mvar Capacity (Per Unit)	Maximum Mvar Capacity (Per Unit)
1	1.025	-9.9	9.9
2	1.045	-0.4	0.5
10	1.050	-0.3	0.6
12	1.015	-0.5	0.5

Table 4: Transformer Data of IEEE 14 Bus System

Transformer Designation	Tap Setting (Per Unit)
5-6	0.932
4-9	0.969
4-7	0.978
7-8	0.958

Table 5: Synchronous Compensator Data of IEEE 14 Bus System

Bus No	Voltage Magnitude (Per Unit)	Minimum Mvar Capacity (Per Unit)	Maximum Mvar Capacity (Per Unit)
3	1.01	0.0	0.4
8	1.09	-0.06	0.24
6	1.07	-0.06	0.24
12	1.015	-0.5	0.5

Table 6: Voltage Independent Load Data of IEEE 14 Bus System

Bus No	Load Active Power (Per Unit)	Load Reactive Power (Per Unit)
2	0.1064	0.0024
3	1.3188	0.266
4	0.6692	0.056
5	0.1064	0.0024
6	0.1568	0.105
9	0.413	0.2324
10	0.126	0.0812
11	0.049	0.0252
12	0.0854	0.0224
13	0.189	0.0812
14	0.2086	0.07

In the next step the voltage independent loads are replaced by voltage dependent loads and the above system is again drawn in Simulink.

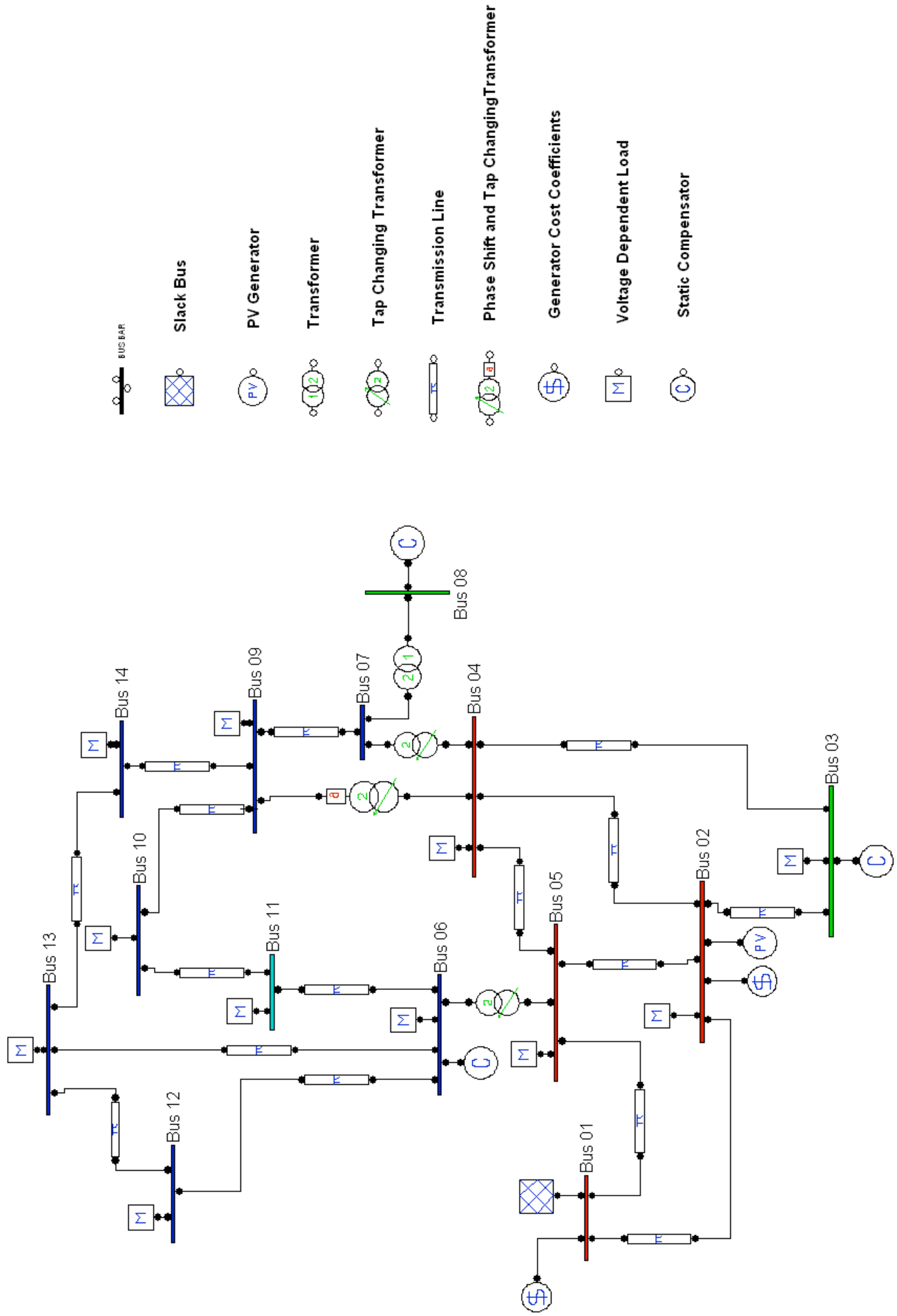

Fig 5: Simulink model of IEEE 14 bus system with voltage dependent loads

Finally the cost functions are provided and simulations are carried out in PSAT.

4.2 Simulation

The above model is simulated in PSAT environment and following results are obtained.

Table 7: Power Flow Data of IEEE 14-bus system without voltage independent load

Bus No	Voltage Magnitude	Angle (in Radians)	Load		Generation	
			MW	MVar	MW	MVar
1	1.2	0	23.2541	17.4424	17.8541	17.4424
2	1.1757	-0.06541	8.6786	32.22	90.0586	50
3	1.1259	-0.21934	11.88	13.4	0.000	40
4	1.123	-0.17063	6.92	5.6	0.000	0.000
5	1.1295	-0.14554	7.64	2.24	0.000	0.000
6	1.1728	-0.26753	5.68	13.5	0.000	24
7	1.1469	-0.2472	0.000	0.000	0.000	0.000
8	1.1527	-0.2472	0.000	24	0.000	24
9	1.1266	-0.28822	4.88	23.24	0.000	0.000
10	1.1249	-0.29034	3.53	8.12	0.000	0.000
11	1.1438	-0.28137	4.9	2.52	0.000	0.000
12	1.1517	-0.28572	7.54	2.24	0.000	0.000
13	1.1433	-0.28741	2.9	8.12	0.000	0.000
14	1.1103	-0.30896	3.86	7	0.000	0.000

Table 8: Total Demand, Losses and Generation cost in case of voltage independent load

Total Generation (in MW)	107.9127
Total Demand (in MW)	91.6627
Total Losses (in MW)	17.76
Generation Cost (₹/Hr)	163.2174

Table 9: Power Flow Data of IEEE 14-bus system with voltage dependent load

Bus No	Voltage Magnitude	Angle (in Radians)	Load		Generation	
			MW	MVar	MW	MVar
1	1.2	0	22.1236	13.2164	15.32	13.2164
2	1.1765	-0.00151	9.1659	29.456	87.0045	50
3	1.1126	-0.15684	10.98	15.5	0.000	24
4	1.187	-0.14521	6.69	7.26	0.000	0.000
5	1.1296	-0.12468	7.234	1.56	0.000	0.000
6	1.1821	-0.02247	7.92	16.43	0.000	40
7	1.1543	-0.31554	0.000	0.000	0.000	0.000
8	1.1452	-0.31554	0.000	24	0.000	24
9	1.1697	-0.31548	4.9	21.84	0.000	0.000
10	1.1129	-0.03149	3.69	6.21	0.000	0.000
11	1.1421	-0.12349	3.69	2.52	0.000	0.000
12	1.1517	-0.26483	6.34	3.4	0.000	0.000
13	1.1597	-0.15496	3.56	4.45	0.000	0.000
14	1.1657	-0.16437	5.976	9.359	0.000	0.000

Table 10: Total Demand, Losses and Generation cost in case of voltage dependent load

Total Generation (in MW)	102.3245
Total Demand (in MW)	89.2695
Total Losses (in MW)	13.055
Generation Cost (₹/Hr)	126.1567

The above results are then used to plot different graphs and analyze the system further.

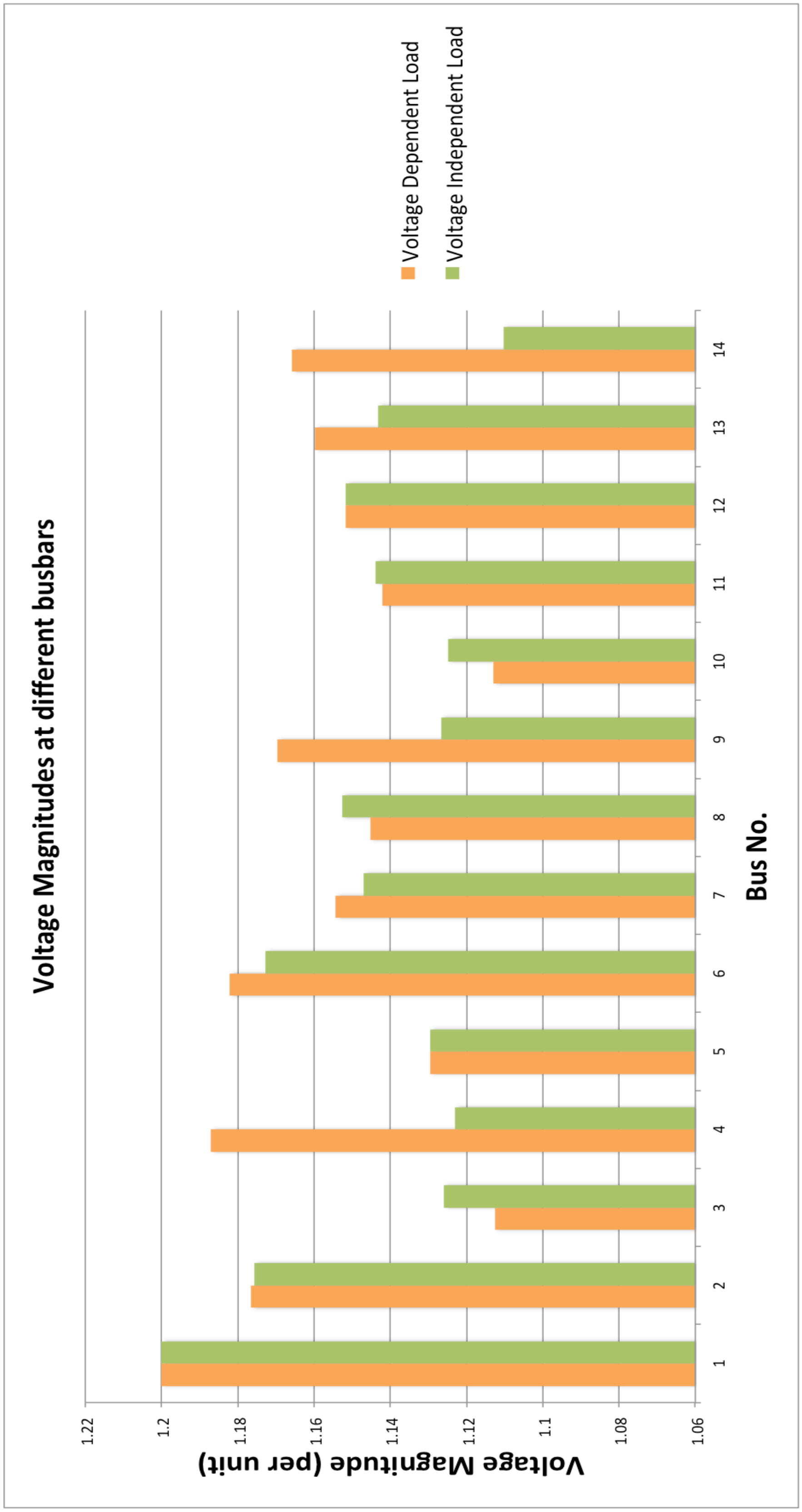

Fig 6: Plot of Voltage magnitudes at different bus bars

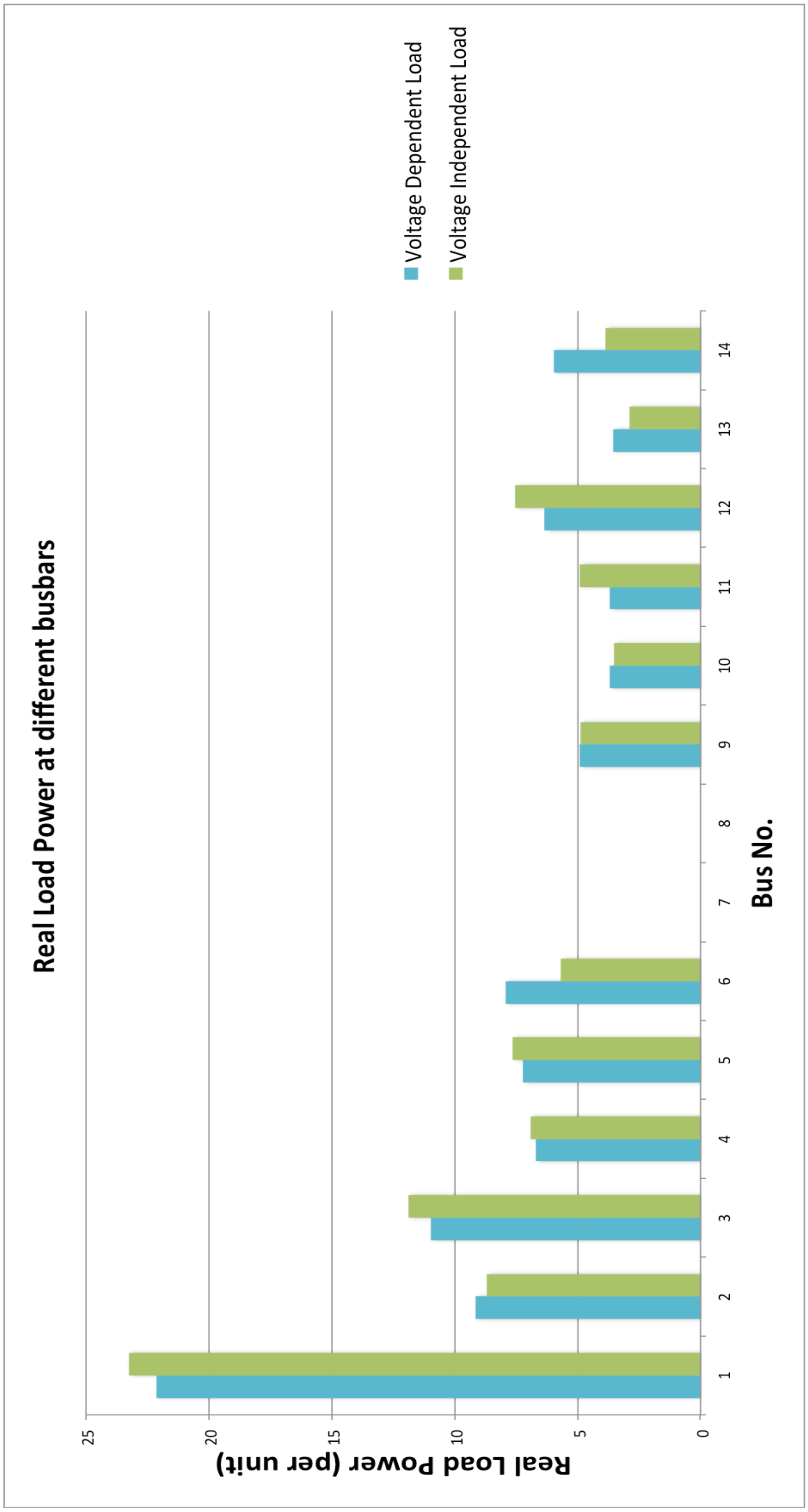

Fig 7: Plot of Real Load Power at different bus bars

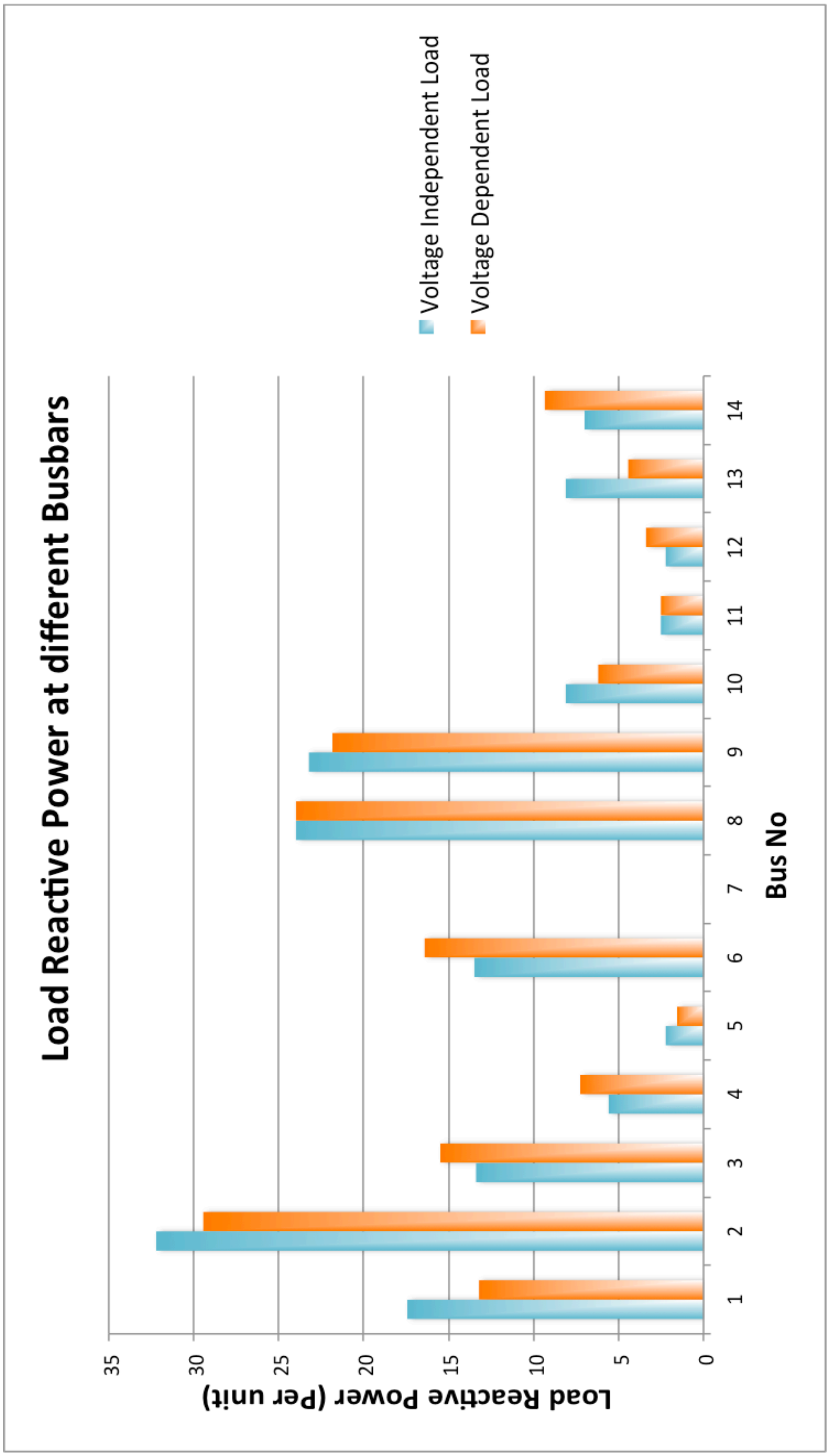

Fig 8: Plot of Reactive Load Power at different bus bars

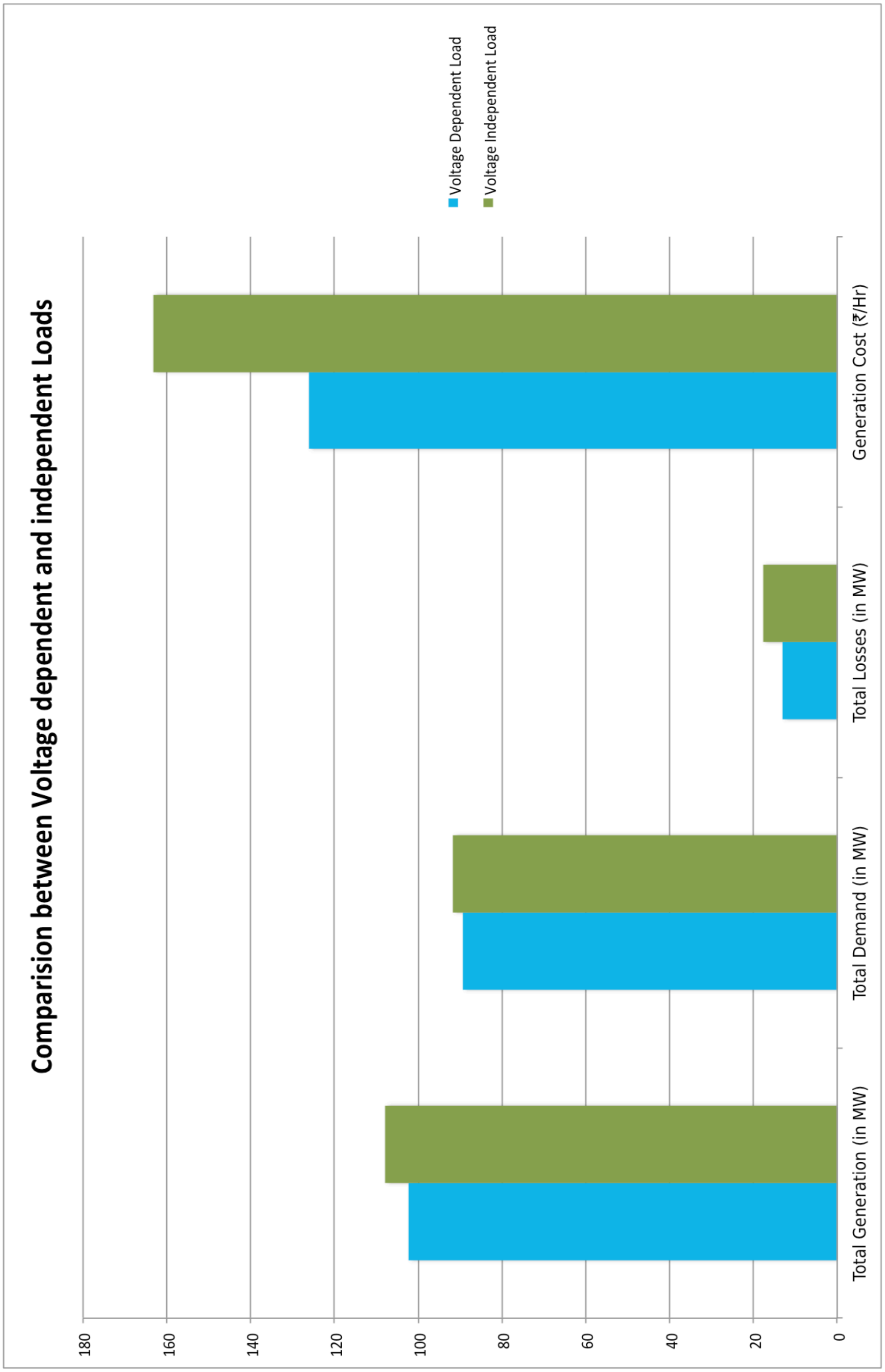

Fig 9: Overall Comparison between Voltage dependent and Independent Loads

4.3 Analysis of Results

4.3.1 Voltage Magnitude

Data from Table 7 and Table 9 are taken and plotted in Fig. 5. The magnitude of voltages at different buses is shown in the plot. It can be observed that, in case of voltage independent loads, the voltage magnitudes are less in value in comparison to the case of voltage dependent loads. In the former case, the active power generation is more pronounced when voltage magnitudes are greater than 1 p.u. Incorporation of voltage dependent loads ensures a flat voltage profile, i.e. the load flow increases voltage magnitudes below 1 p.u and decreases those above 1 p.u.

4.3.2 Swing bus Active Power

Swing bus active power difference in case of both the type of loads is 2.5 %. This is quite high in value and can be accounted for net decrease in power generation and hence the reduced cost of operation. The swing bus active power difference depends both on voltage and phase angle difference and practically is very difficult to predict from conventional load flow analysis without incorporating voltage dependent loads.

4.3.3 Generator Reactive Power

The reactive power differences lie in the range of 0.04 to 0.16 p.u. , i.e. 4 % to 16 %. This range is even higher than that of swing bus active power difference. In one case a generator bus that had reached the reactive-power limits in the conventional load-flow analysis did not do so when the loads were modeled to vary with voltage. The generator reactive power difference also depends on voltage magnitudes and phase angle differences.

4.3.4 Load Active Power

Load active powers at different buses are plotted in Fig. 6. As it is evident from the plot, the active power consumption at different bus bars in case of voltage dependent and independent are not the same. In case of the former, the real power consumption is less in comparison to the latter. Decrease in active power consumption implies less loss and better stability and security of the system.

4.3.5 Load Reactive Power

The reactive powers at different bus bars don’t follow any particular trend, i.e. at some bus bars they’ve higher value in case of voltage dependent loads and at some, the values are lower. But essentially the difference range is 0.6 % to 4.2 %.

4.3.6 Overall Comparison

The overall comparison of total demand, losses, generation and generation costs are plotted on Fig. 8. It should be noted that, in case of load modeling each of the above mentioned quantity has a lower value in comparison to that of conventional load flow. There is significant decrease in generation cost and total losses. A basic cost analysis is given below to emphasize the importance load modeling.

Generation cost in case of voltage independent loads = 163.2174 ₹/Hr

Generation cost in case of voltage dependent loads = 126.1567 ₹/Hr

Difference in generation cost in an hour = 37.0607 ₹

Difference in generation cost in a day = 37.0607*24 = 889.4568 ₹

Difference in generation cost in a year = 889.4568*365 = 324651.7 ₹

4.4 Conclusion

This thesis has reported on results of an investigation of the effects of incorporating load models, which represent the variation of active and reactive power demands with voltage at respective bus bars in OPF analysis. A computational experiment using a standard IEEE 14 bus system was conducted and the effects of load modeling were also included in the experiment.

It was seen that the fuel cost difference was the most pronounced effect of load modeling. The heavier the system loading, the lower is the fuel cost difference. Calculations show that, the cost of generation for a whole year can decrease significantly by implementing load models. The calculations are more accurate and system stability and security increase with incorporation of voltage dependent load models.

The modeling of reactive power has a greater effect on voltage difference, whereas the modeling of active power is more pronounced in case of phase angle differences.

The required total generation power doesn't vary widely when load models are incorporated but it's this small difference that affects generation cost difference and total losses. This can be explained by saying that, total generation cost function has a square term of generation power in it.

The difference in power loss is in the order of 4 %, when active and reactive powers are modeled. Hence it's advantageous to incorporate load models in OPF studies for predicting total power losses.

Reference and Appendix

5.1 Appendix (Power System Analysis Toolbox - PSAT)

PSAT Is a MATLAB toolbox for power system analysis and control. PSAT includes Power flow, Optimal Power Flow (OPF), Continuation Power flow etc. A Graphical User Interface (GUI) can assess all the above operations.

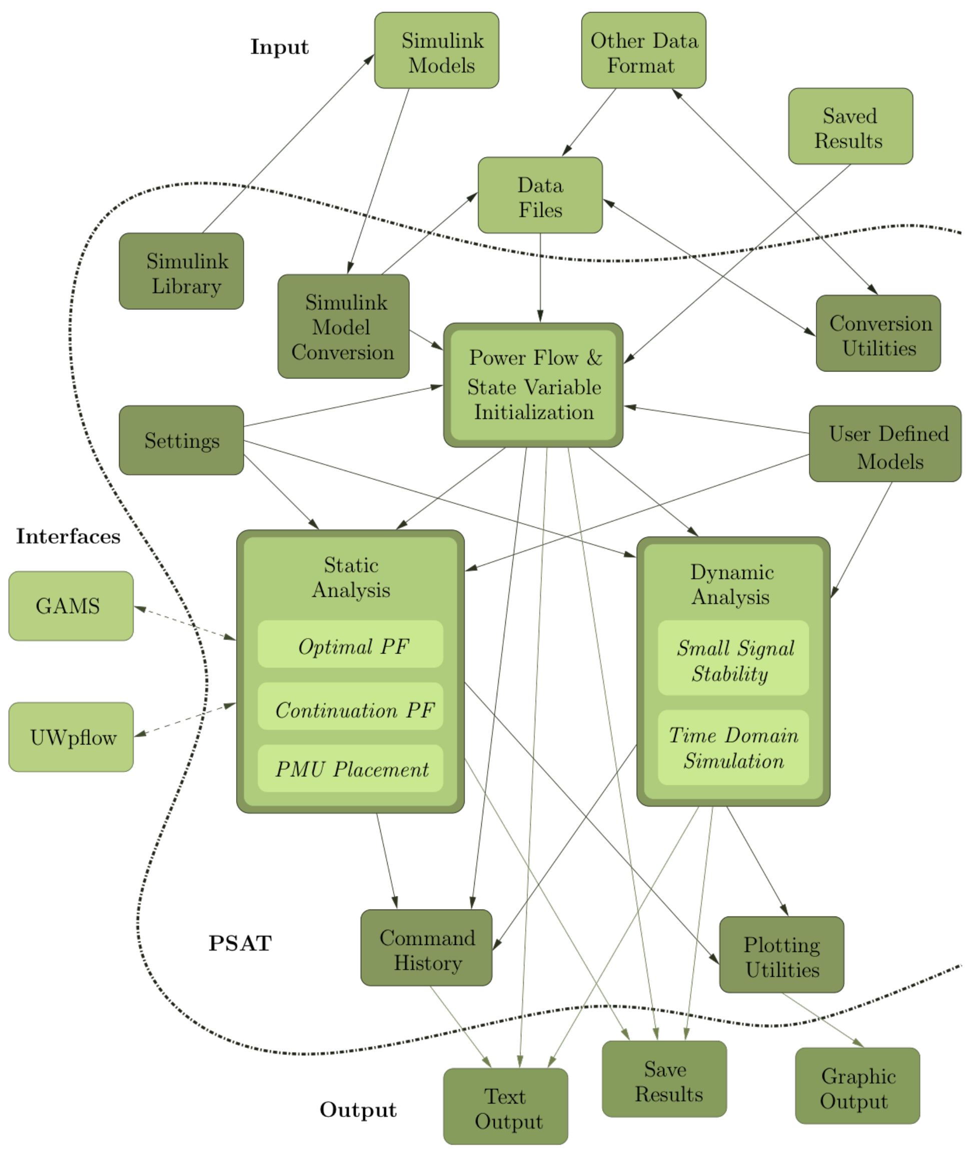

Fig 10: Basic PSAT operations

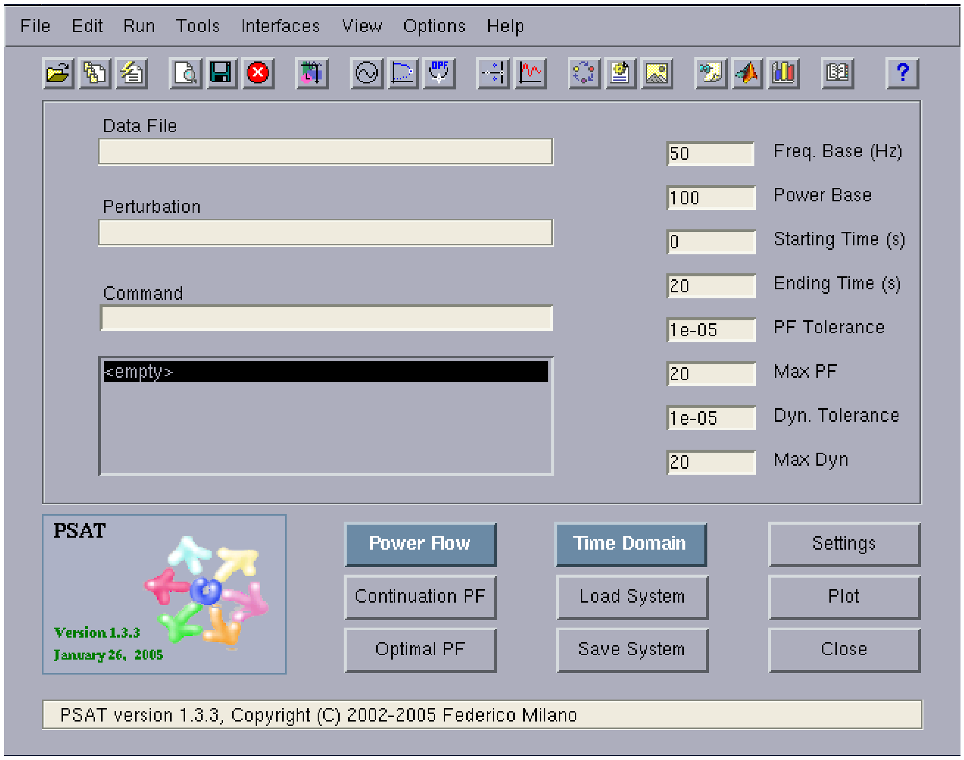

Fig 11: Main GUI of PSAT

Fig. 1o shows the main GUI of PSAT. Various functions or operations are performed using the command buttons showed in the figure.

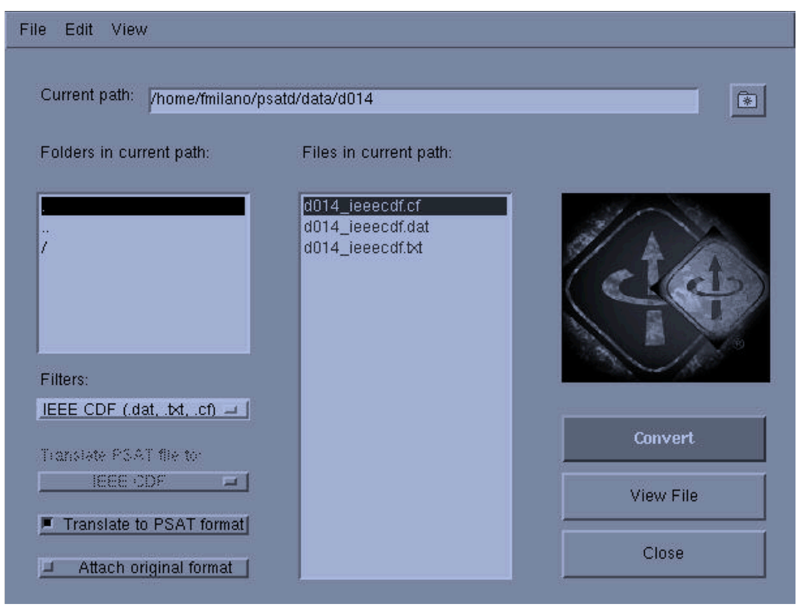

Fig 12: GUI for data format conversion in PSAT

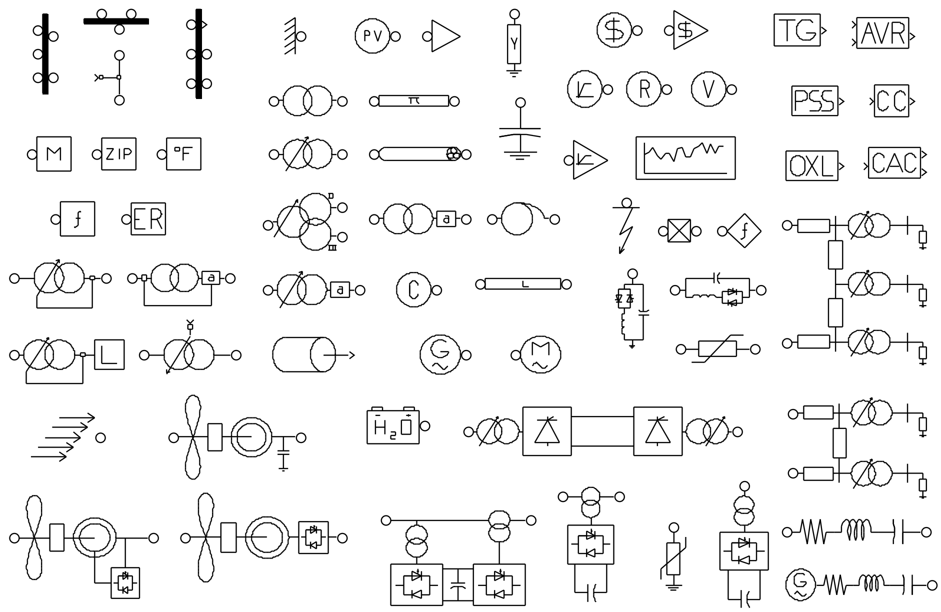

Fig 13: PSAT Simulink Library

PSAT allows drawing electrical power systems by means of Simulink blocks. The computational engine is purely MATLAB based and Simulink is used as a graphical tool for the simulations. For every command in PSAT a MATLAB code is executed in background and results are displayed in the result (report window) window of the application.

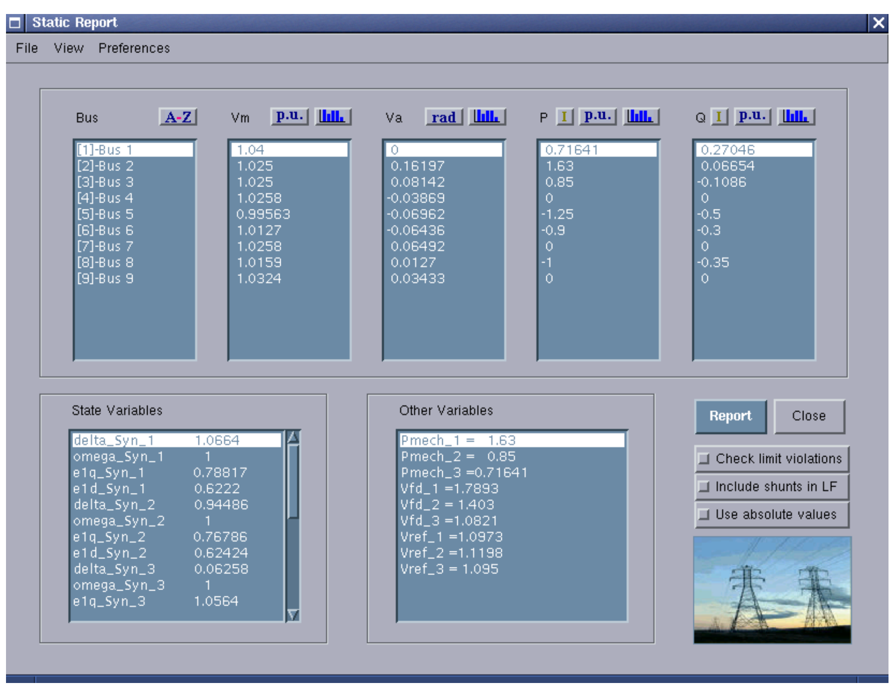

Fig 14: PSAT Result Window

Given below are the codes that are executed, for each function that is performed by PSAT.

LFNEWTON

This function is used for Newton-Raphson solution of the given Load Flow problem.

```
ns=0; ng=0; Vm=0; delta=0; yload=0; deltad=0;
nbus = length(busdata(:,1));
for k=1:nbus
n=busdata(k,1);
kb(n)=busdata(k,2); Vm(n)=busdata(k,3); delta(n)=busdata(k, 4);
Pd(n)=busdata(k,5); Qd(n)=busdata(k,6); Pg(n)=busdata(k,7); Qg(n) =
busdata(k,8);
Qmin(n)=busdata(k, 9); Qmax(n)=busdata(k, 10);
Qsh(n)=busdata(k, 11);
    if Vm(n) <= 0  Vm(n) = 1.0; V(n) = 1 + j*0;
    else delta(n) = pi/180*delta(n);
         V(n) = Vm(n)*(cos(delta(n)) + j*sin(delta(n)));
         P(n)=(Pg(n)-Pd(n))/basemva;
         Q(n)=(Qg(n)-Qd(n)+ Qsh(n))/basemva;
         S(n) = P(n) + j*Q(n);
    end
end
for k=1:nbus
if kb(k) == 1, ns = ns+1; else, end
if kb(k) == 2 ng = ng+1; else, end
ngs(k) = ng;
nss(k) = ns;
end
Ym=abs(Ybus); t = angle(Ybus);
m=2*nbus-ng-2*ns;
maxerror = 1; converge=1;
iter = 0;
% Start of iterations
clear A  DC   J  DX
while maxerror >= accuracy & iter <= maxiter % Test for max. power mismatch
for i=1:m
for k=1:m
   A(i,k)=0;      %Initializing Jacobian matrix
end, end
iter = iter+1;
for n=1:nbus
nn=n-nss(n);
lm=nbus+n-ngs(n)-nss(n)-ns;
J11=0; J22=0; J33=0; J44=0;
   for i=1:nbr
     if nl(i) == n | nr(i) == n
        if nl(i) == n,  l = nr(i); end
        if nr(i) == n,  l = nl(i); end
        J11=J11+ Vm(n)*Vm(l)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));
        J33=J33+ Vm(n)*Vm(l)*Ym(n,l)*cos(t(n,l)- delta(n) + delta(l));
        if kb(n)~=1
        J22=J22+ Vm(l)*Ym(n,l)*cos(t(n,l)- delta(n) + delta(l));
        J44=J44+ Vm(l)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));
        else, end
        if kb(n) ~= 1  & kb(l) ~=1
        lk = nbus+l-ngs(l)-nss(l)-ns;
```

```
        ll = l -nss(l);
      % off diagonalelements of J1
        A(nn, ll) =-Vm(n)*Vm(l)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));
              if kb(l) == 0  % off diagonal elements of J2
              A(nn, lk) =Vm(n)*Ym(n,l)*cos(t(n,l)- delta(n) + delta(l));end
              if kb(n) == 0  % off diagonal elements of J3
              A(lm, ll) =-Vm(n)*Vm(l)*Ym(n,l)*cos(t(n,l)- delta(n)+delta(l));
end
              if kb(n) == 0 & kb(l) == 0  % off diagonal elements of  J4
              A(lm, lk) =-Vm(n)*Ym(n,l)*sin(t(n,l)- delta(n) + delta(l));end
        else end
     else , end
   end
   Pk = Vm(n)^2*Ym(n,n)*cos(t(n,n))+J33;
   Qk = -Vm(n)^2*Ym(n,n)*sin(t(n,n))-J11;
   if kb(n) == 1 P(n)=Pk; Q(n) = Qk; end   % Swing bus P
     if kb(n) == 2  Q(n)=Qk;
         if Qmax(n) ~= 0
           Qgc = Q(n)*basemva + Qd(n) - Qsh(n);
           if iter <= 7                     % Between the 2th & 6th iterations
              if iter > 2                   % the Mvar of generator buses are
                if Qgc  < Qmin(n),          % tested. If not within limits Vm(n)
                Vm(n) = Vm(n) + 0.01;       % is changed in steps of 0.01 pu to
                elseif Qgc  > Qmax(n),      % bring the generator Mvar within
                Vm(n) = Vm(n) - 0.01;end % the specified limits.
              else, end
           else,end
         else,end
     end
   if kb(n) ~= 1
     A(nn,nn) = J11;  %diagonal elements of J1
     DC(nn) = P(n)-Pk;
   end
   if kb(n) == 0
     A(nn,lm) = 2*Vm(n)*Ym(n,n)*cos(t(n,n))+J22;  %diagonal elements of J2
     A(lm,nn)= J33;        %diagonal elements of J3
     A(lm,lm) =-2*Vm(n)*Ym(n,n)*sin(t(n,n))-J44;  %diagonal of elements of J4
     DC(lm) = Q(n)-Qk;
   end
end
DX=A\DC';
for n=1:nbus
  nn=n-nss(n);
  lm=nbus+n-ngs(n)-nss(n)-ns;
    if kb(n) ~= 1
    delta(n) = delta(n)+DX(nn); end
    if kb(n) == 0
    Vm(n)=Vm(n)+DX(lm); end
 end
  maxerror=max(abs(DC));
     if iter == maxiter & maxerror > accuracy
   fprintf('\nWARNING: Iterative solution did not converged after ')
   fprintf('%g', iter), fprintf(' iterations.\n\n')
   fprintf('Press Enter to terminate the iterations and print the results 
\n')
   converge = 0; pause, else, end

end
```

```
if converge ~= 1
   tech= ('                      ITERATIVE SOLUTION DID NOT CONVERGE'); else,
   tech=('                    Power Flow Solution by Newton-Raphson Method');
end
V = Vm.*cos(delta)+j*Vm.*sin(delta);
deltad=180/pi*delta;
i=sqrt(-1);
k=0;
for n = 1:nbus
     if kb(n) == 1
     k=k+1;
     S(n)= P(n)+j*Q(n);
     Pg(n) = P(n)*basemva + Pd(n);
     Qg(n) = Q(n)*basemva + Qd(n) - Qsh(n);
     Pgg(k)=Pg(n);
     Qgg(k)=Qg(n);     %june 97
     elseif  kb(n) ==2
     k=k+1;
     S(n)=P(n)+j*Q(n);
     Qg(n) = Q(n)*basemva + Qd(n) - Qsh(n);
     Pgg(k)=Pg(n);
     Qgg(k)=Qg(n);  % June 1997
  end
yload(n) = (Pd(n)- j*Qd(n)+j*Qsh(n))/(basemva*Vm(n)^2);
end
busdata(:,3)=Vm'; busdata(:,4)=deltad';
Pgt = sum(Pg);  Qgt = sum(Qg); Pdt = sum(Pd); Qdt = sum(Qd); Qsht = sum(Qsh);

%clear A DC DX  J11 J22 J33 J44 Qk delta lk ll lm
%clear A DC DX  J11 J22 J33  Qk delta lk ll lm
```

BLOSS

This function obtains the B co-efficients from the loss formula.

```
clear B B0 B00
Zbus=inv(Ybus);
ngg=0;
I=-1/basemva*(Pd-j*Qd)./conj(V); %new
ID= sum(I);  %new

for k=1:nbus
  if kb(k)== 0
%     I(k) = conj(S(k))/conj(V(k));
%    else, ngg=ngg+1; I(k)=0;  end
    else, ngg=ngg+1;  end
   if kb(k)==1 ks=k; else, end
end
%ID= sum(I);
d1=I/ID;
DD=sum(d1.*Zbus(ks,:));  %new
kg=0; kd=0;
for k=1:nbus
    if kb(k)~=0
```

```
        kg=kg+1;
        t1(kg) = Zbus(ks,k)/DD;    %new
        else, kd=kd+1;
        d(kd)=I(k)/ID;
        end
end
nd=nbus-ngg;
C1g=zeros(nbus, ngg);
kg=0;
for k=1:nbus
    if kb(k)~=0
    kg=kg+1;
        for m=1:ngg
            if kb(m)~=0
             C1g(k, kg)=1;
            else, end
        end
    else,end
end
C1gg=eye(ngg,ngg);
C1D=zeros(ngg,1);
C1=[C1g,conj(d1)'];
C2gD=[C1gg; -t1];
CnD=[C1D;-t1(1)];
C2=[C2gD,CnD];
C=C1*C2;
kg=0;
for k=1:nbus
    if kb(k)~=0
    kg=kg+1;
    al(kg)=(1-j*((Qg(k)+Qsh(k))/Pg(k)))/conj(V(k));   %new
    else,end
end
alp=[al, -V(ks)/Zbus(ks,ks)];
for k=1:ngg+1
        for m=1:ngg+1
        if k==m
        alph(k,k)=alp(k);
        else, alph(k,m)=0;end
end,end
T = alph*conj(C)'*real(Zbus)*conj(C)*conj(alph);
BB=0.5*(T+conj(T));
for k=1:ngg
        for m=1:ngg
        B(k,m)=BB(k,m);
        end
        B0(k)=2*BB(ngg+1,k);
end
B00=BB(ngg+1,ngg+1);
B, B0, B00
PL = Pgg*(B/basemva)*Pgg'+B0*Pgg'+B00*basemva;
fprintf('Total system loss = %g MW \n', PL)
clear I BB C C1 C1D C1g C1gg C2 C2gD CnD DD ID T al alp alph t1 d d1 kd kg ks
nd ng
```

DISPATCH

This program solves the coordination equation for economic scheduling of generation.

```
clear Pgg
if exist('Pdt')~=1
Pdt = input('Enter total demand Pdt = ');
else, end
if exist('cost')~=1
cost = input('Enter the cost matrix, cost = ');
else, end
ngg = length(cost(:,1));
if exist('mwlimits')~=1
mwlimits= [zeros(ngg, 1), inf*ones(ngg,1)];
else, end
if exist('B')~=1
B = zeros(ngg, ngg);
else, end
if exist('B0')~=1
B0=zeros(1, ngg);
else, end
if exist('B00')~=1
B00=0;
else, end
if exist('basemva')~=1
basemva=100;
else, end
clear Pgg
Bu=B/basemva; B00u=basemva*B00;
alpha=cost(:,1); beta=cost(:,2); gama = cost(:,3);
Pmin=mwlimits(:,1); Pmax=mwlimits(:,2);
wgt=ones(1, ngg);
if Pdt > sum(Pmax)
Error1 = ['Total demand is greater than the total sum of maximum generation.'
          'No feasible solution.  Reduce demand or correct generator
limits.'];
disp(Error1), return
elseif Pdt < sum(Pmin)
Error2 = ['Total demand is less than the total sum of minimum generation.
'
          'No feasible solution. Increase demand or correct generator
limits.'];
disp(Error2), return
else, end
iterp = 0;                                 % Iteration counter
DelP = 10;              % Error in DelP is set to a high value

E=Bu;
if exist('lambda')~=1
lambda=max(beta);
end
while abs(DelP)  >= 0.0001  & iterp < 200     % Test for convergence
iterp = iterp + 1;                          % No. of iterations
for k=1:ngg
    if wgt(k) == 1
       E(k,k) = gama(k)/lambda + Bu(k,k);
       Dx(k) = 1/2*(1 - B0(k)- beta(k)/lambda);
       else, E(k,k)=1;  Dx(k) = 0;
            for m=1:ngg
               if m~=k
```

```
                E(k,m)=0;
                else,end
              end
       end
end
PP=E\Dx';
for k=1:ngg
if wgt(k)==1
   Pgg(k) = PP(k);
   else,end
end
Pgtt = sum(Pgg);
PL=Pgg*Bu*Pgg'+B0*Pgg'+B00u;
DelP =Pdt+PL -Pgtt ;                                    %Residual
for k = 1:ngg
   if Pgg(k) > Pmax(k) & abs(DelP) <=0.001,
   Pgg(k) = Pmax(k); wgt(k) = 0;
   elseif Pgg(k) < Pmin(k) & abs(DelP) <= 0.001
   Pgg(k) = Pmin(k); wgt(k) = 0;
   else, end
end
PL=Pgg*Bu*Pgg'+B0*Pgg'+B00u;
DelP =Pdt +PL - sum(Pgg);                                %Residual
  for k=1:ngg
  BP = 0;
     for m=1:ngg
         if m~=k
            BP = BP + Bu(k,m)*Pgg(m);
            else, end
     end
  grad(k)=(gama(k)*(1-B0(k))+Bu(k,k)*beta(k)-
2*gama(k)*BP)/(2*(gama(k)+lambda*Bu(k,k))^2);
  end
sumgrad=wgt*grad';
Delambda = DelP/sumgrad;                   % Change in variable
lambda = lambda + Delambda;                % Successive solution
end
fprintf('Incremental cost of delivered power (system lambda) = %9.6f $/MWh
\n', lambda);
fprintf('Optimal Dispatch of Generation:\n\n')
disp(Pgg')
%fprintf('Total system loss = %g MW \n\n', PL)
ng=length(Pgg);
n=0;
if exist('nbus')==1 | exist('busdata')==1
  for k=1:nbus
     if kb(k)~=0
        n=n+1;
        if n <= ng
        busdata(k,7)=Pgg(n); else, end
     else , end
  end
  if n == ng
     for k=1:nbus
         if kb(k)==1
         dpslack = abs(Pg(k)-busdata(k,7))/basemva;
         fprintf('Absolute value of the slack bus real power mismatch,
dpslack = %8.4f pu \n', dpslack)
         else, end
```

```
     end
   else, end
 else, end
clear BP Dx DelP Delambda E PP grad sumgrad wgt Bu B00u B B0 B00
```

BUSOUT

This program prints power flow solutions in tabular form.

```
%clc
disp(tech)
fprintf('                      Maximum Power Mismatch = %g \n', maxerror)
fprintf('                             No. of Iterations = %g \n\n', iter)
head =['    Bus  Voltage  Angle    ------Load------    ---Generation---
Injected'
       '    No.  Mag.     Degree     MW       Mvar       MW       Mvar
Mvar '
       '
'];
disp(head)
for n=1:nbus
     fprintf(' %5g', n), fprintf(' %7.3f', Vm(n)),
     fprintf(' %8.3f', deltad(n)), fprintf(' %9.3f', Pd(n)),
     fprintf(' %9.3f', Qd(n)),  fprintf(' %9.3f', Pg(n)),
     fprintf(' %9.3f ', Qg(n)), fprintf(' %8.3f\n', Qsh(n))
end
    fprintf('      \n'), fprintf('    Total              ')
    fprintf(' %9.3f', Pdt), fprintf(' %9.3f', Qdt),
    fprintf(' %9.3f', Pgt), fprintf(' %9.3f', Qgt), fprintf(' %9.3f\n\n',
Qsht)
```

GENCOST

This program calculates the total generation cost.

```
if exist('Pgg')~=1
Pgg=input('Enter the scheduled real power gen. in row matrix ');
else,end
if exist('cost')~=1
cost = input('Enter the cost function matrix ');
else, end
ngg = length(cost(:,1));
Pmt = [ones(1,ngg); Pgg; Pgg.^2];
for i = 1:ngg
costv(i) = cost(i,:)*Pmt(:,i);
end
totalcost=sum(costv);
fprintf('\nTotal generation cost = % 10.2f $/h \n', totalcost)
```

YBUS

This program calculates the bus admittance matrix.

```
function[Ybus] = ybus(zdata)
nl=zdata(:,1); nr=zdata(:,2); R=zdata(:,3); X=zdata(:,4);
nbr=length(zdata(:,1)); nbus = max(max(nl), max(nr));
Z = R + j*X;                              %branch impedance
y= ones(nbr,1)./Z;                       %branch admittance
Ybus=zeros(nbus,nbus);           % initialize Ybus to zero
for k = 1:nbr;    % formation of the off diagonal elements
    if nl(k) > 0 & nr(k) > 0
    Ybus(nl(k),nr(k)) = Ybus(nl(k),nr(k)) - y(k);
    Ybus(nr(k),nl(k)) = Ybus(nl(k),nr(k));
    end
end
for n = 1:nbus       % formation of the diagonal elements
    for k = 1:nbr
    if nl(k) == n | nr(k) == n
    Ybus(n,n) = Ybus(n,n) + y(k);
    else, end
    end
end
```

5.1 References

[1]. C. L. Wadhwa (2009), “Electrical Power Systems”, Chap 18, Chap 19.

[2]. Dommel, H.W. and Tinney, W. F. “Optimal Power Flow Solutions”, IEE TRANSACTIONS ON POWER APPARTUS AND SYSTEM, Vol PAS-87, No. 10, OCTOBER 1968

[3]. Dias, L. G. “Effects of active and reactive power modeling on optimal load flows”, IEE PROCEEDINGS, Vol. 136, Pt. C, No. 5, September 1989

[4]. Adeline Chan, W. Z. “ Power system Load Modelling”, The University of Queensland.

[5]. D. P. Nagrath, I. J. Kothari, “Modern Power Flow Analysis”, Chap 6, Chap 7

[6]. Saadat H.(2010), "Power System Analysis", Chap 6, Chap 7.

[7]. Milano, Federico, “Power System Analysis Toolbox”, July 2005